Fermilab

TM-1043
0102.000
January 1981

A HIGH INTENSITY ACCELERATOR FACILITY

by

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I. INTRODUCTION

Discussions of high energy versus high intensity were pursued vigorously as far back as 1955 at the Midwestern Universities Research Association.[1] The heated dispute at the time was focused on a contest between the merits of one against the other. Now 25 years later the ever rising energy will soon reach 2 TeV in the $\bar{p}p$ colliding beams at Fermilab, equivalent to a fixed target beam energy of some 2000 TeV, and a consistent standard model of elementary particles and their interactions evolved as a consequence. There is no more doubt that the energy frontier should be advanced with all vigor. It is, therefore, doubly significant and convincing when interests are mounting for a high intensity proton accelerator facility at some modest energy.

The need for such a facility has been well documented by the interesting new physics reported at this and other workshops and symposia.[2] An energy between 10 and 20 GeV would be adequate for most of the experiments envisioned. Much above 20 GeV we enter the energy range which is serviced by the so-called high energy accelerators. The unique requirement for this "medium" energy facility is the high intensity. As usual, the intensity desired is the higher the better limited only by practical considerations, but some two orders of magnitude higher than that now available is considered sufficient and justification enough for a new facility. We choose for discussion here an energy of 16 GeV (rather arbitrary) and an average beam current of 100 μA ($6\times10^{14}\text{sec}^{-1}$). The practical considerations leading to this choice of beam current are:

(a) At 16 GeV and 100 μA the beam power is 1.6 MW. To accelerate such a beam one needs ~3 MW of rf power or ~6 MW of ac power. This large power

*Operated by the Universities Research Association, Inc., under contract with the U.S. Department of Energy.

consumption for rf alone implies rather high operating cost for the facility. Furthermore, the cost of the rf supply, typically \$3/watt, is already about \$10 million.

(b) Targetting the 1.6 MW beam, although possible, is not trivial. To go much beyond this would make targetting extremely difficult.

(c) An intensity of 100 μA is about two orders of magnitude higher than that available from existing accelerators. It will be seen later that this high intensity is close to the limiting capability of an inexpensive type of accelerator, the fast cycling synchrotron. To get much higher intensity one must take a step toward a more costly type of accelerator.

The potential of such a proton beam for physics can be illustrated by the following considerations.

(a) With primary beam on target, taking a rather large beam cross-sectional area of 1 cm^2, hence a conservative beam flux of $6\times10^{14}cm^{-2}sec^{-1}$, and a 1 mole target we get a luminosity of

$$L = (6\times10^{23})\times(6\times10^{14}cm^{-2}sec^{-1}) = 3.6\times10^{38}cm^{-2}sec^{-1}$$

which is very large indeed compared to the $<10^{31}cm^{-2}sec^{-1}$ available from colliding beams. Moreover, the reaction cross-sections considered here are likely to be much larger than those of the events studied on the colliders.

(b) For secondary beams we take as an example kaon beams at 1 and 2 GeV/c. This was studied in 1976.[3] Taking forward production and an acceptance solid angle of 24 msr (5^o semi-cone angle) we get

	Number per GeV/c per sec	
Momentum	K^+	K^-
1 GeV/c	$1.4\times10^{12}\times E_T$	$0.4\times10^{12}\times E_T$
2 GeV/c	$1.6\times10^{12}\times E_T$	$0.6\times10^{12}\times E_T$

where E_T is the targetting efficiency. These are, again, very high intensities.

II. GENERAL CONSIDERATIONS

A. Type of Accelerator

(1) Linac is capable of the highest intensity. For application as source of spallation neutrons for breeding fissile fuels or for neutron damage studies

intensities as high as 300 mA have been contemplated. On the other hand, it is also the most costly. At the current unit cost of about 10 eV per dollar, a 16 GeV linac would cost well over $1 billion.

(2) Microtron[4] and FFAG[5] (Fixed-Field Alternating Gradient ring accelerator) are both capable ‾ this and, perhaps, higher intensities. But a great deal of R&D is requireu before the construction of either type of accelerator can proceed. Furthermore, although not to the extreme as the linac, these accelerators still tend to be rather costly.

(3) Fast cycling synchrotron is straightforward and the most inexpensive, but is limited in intensity. To get an average intensity of 6×10^{14} protons/sec we need 1×10^{13} p/pulse at a 60 Hz pulse rate. Normally this is close to the limit of the capability of a fast cycling synchrotron. However, if one can use the 800 MeV LAMPF as injector this intensity is easily obtainable.

The space charge limited proton number in a synchrotron is given by

$$N = \frac{2\,\Delta\nu}{r_p}\,\beta^2\gamma^3\ \varepsilon = (1.17\times10^{18}\mathrm{m}^{-1})\varepsilon$$

where

r_p = classical radius of proton = 1.54×10^{-18}m

$\Delta\nu$ = allowable tune shift = 0.2

$\beta^2\gamma^3$ = relativistic kinematic factor = 4.5 (at 800 MeV)

ε = beam emittance.

Thus to get $N = 10^{13}$ one needs an emittance of only $\varepsilon \approx 8.5\times10^{-6}$m $\approx 2.7\pi$ mm-mrad which is quite easily contained in a synchrotron. On the other hand, if instead of 800 MeV the injection is from a conventional 200 MeV Alvarez linac, the $\beta^2\gamma^3$ factor is down by a factor of ~8. The beam emittance, hence the magnet aperture must then be increased by a factor 8. Although possible, this requires a substantially more expensive magnet system.

Aside from this simple space charge detuning there are many other high intensity effects causing instability in the beam. But experiences show that all these effects are either avoidable or curable at intensities of 1 or 2×10^{13} p/pulse.

B. Synchrotron Features

The only choices requiring discussion are the type and peak field of the magnet system.

(1) We choose conventional instead of superconducting magnets. In the first place, the highest ramp-rate obtained for any superconducting magnet is about $\frac{1}{2}$ Hz. To obtain 6×10^{14} p/sec this requires 1.2×10^{15} p/pulse, much too high for beam stability and for the stability of the superconducting magnets against quenching by stray beam.

Even if, somehow, one were able to keep the magnets superconducting when pulsed at 60 Hz, the ac loss in these magnets will be entirely too high. If the Fermilab Tevatron magnets were used for 16 GeV the ac loss would be ~8.5 kJ/cycle or ~500 kW at 60 Hz. To remove this heat at 4 K one needs approximately 150 MW of electrical power to run the refrigerator. For this reason also, it is impractical to pulse a superconducting magnet ring at rates much higher than 1 Hz.

(2) The peak field B should not be too high. This is because:

(a) magnet cost $\propto$ magnet volume
$\propto$ cross-sectional area x length $\propto B^2 \times \frac{1}{B} \propto B$

(b) power supply cost $\propto$ stored energy in magnet
$\propto$ energy density x aperture x length
$\propto B^2 \times 1 \times \frac{1}{B} \propto B$ (for fixed aperture).

Hence the cost of both the magnets and their power supplies goes down as B is reduced. This should, however, be compromised with the rising cost of the synchrotron tunnel and utilities in the tunnel which is roughly proportional to the ring circumference. In addition, the cost of the rf cavities being proportional to the voltage is also proportional to the circumference. (The cost of the rf supply is, however, proportional to the power.) A nearly optimal compromise is $B \cong 7$ kG.

We will use combined function magnets. This eliminates the need of space for quadrupoles, hence leads to a smaller circumference of the ring.

C. <u>Spill-Stretcher Ring</u>

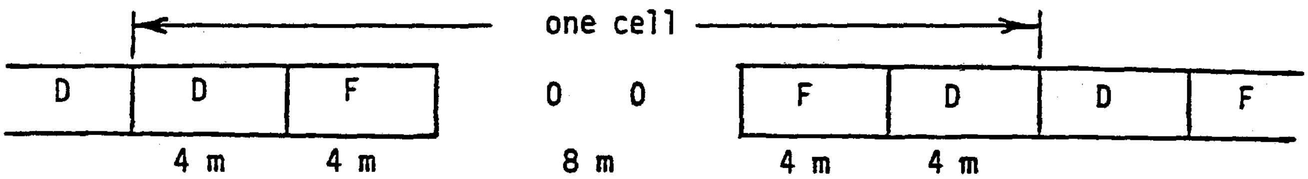
For slow beam spill we will need a separate spill-stretcher ring. This ring will have the same circumference as the synchrotron and will be installed in the same tunnel either above or below the synchrotron. This ring will be operated dc at 16 GeV and is hence ideal for the application of superconducting magnets.

It should be emphasized that superconductors are basically not capable of pulsed operation. The chief and crucial advantage of superconducting magnets is the more than 200-fold power savings compared to conventional magnets when operated dc. The factor ~2 in maximum field over that of conventional magnets is nice but certainly not critical.

III. SYNCHROTRON DESIGN PARAMETERS

A. Ring Magnet Lattice

We shall split a focusing-defocusing cell in the middle of the focusing magnet to insert a long straight section and adjust the magnet gradients to give a phase advance per cell $\mu \cong 90^{\circ}$. These choices will facilitate injection and extraction of the beam. For a high intensity synchrotron clean injection and extraction are essential to keep induced radioactivity low so that hands-on maintenance is possible after prolonged periods of operation. After some cutting and fitting we come to the following cell structure and beam containment parameters. The cell shown is obviously very much stylized. Small gaps between all magnets are needed to accommodate coil ends, correction magnets, beam sensors, etc. However, for the present only the roughest zeroth order approximate values of the parameters are necessary.



Length of DFOOFD cell = 24 m	No. of cells = 32
Ring circumference ($2\pi R$) = 768 m	Radius (R) = 122 m
Total magnet length ($2\pi\rho$) = 512 m	Bending radius (ρ) = 81.5 m

	Initial	Final
Kinetic energy (T)	800 MeV	16 GeV
Bending field (B)	0.60 kG	6.9 kG
Revolution frequency (F)	0.33 MHz	0.39 MHz

Field gradients (B'/B) = $\pm 2.7\ m^{-1}$

Phase advance/cell (μ) = 93° Tune (ν) = 8¼

Amplitude function		β_h (horizontal)	β_v (vertical)
	Mid DD	7.3 m	43 m
	Mid OO	23 m	8.8 m
	Max. D	15 m	43 m
	Max. F	24 m	25 m

B. Magnet Aperture and Space Charge Limit

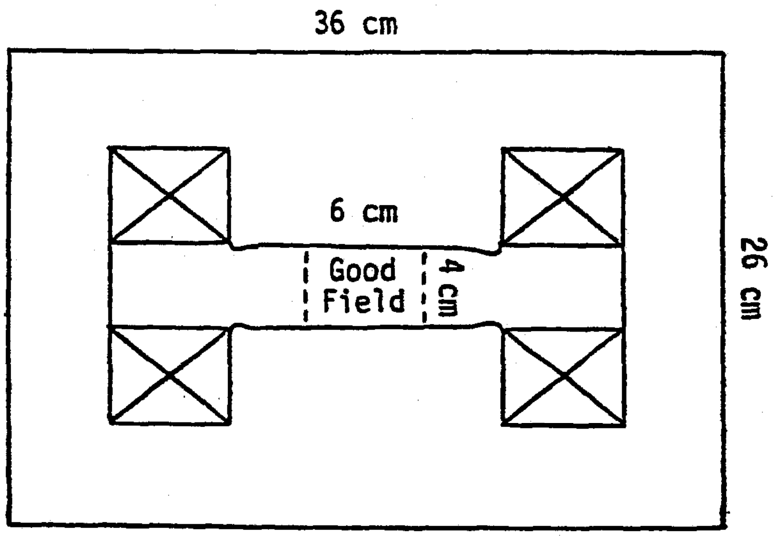
We shall assume a conservative good-field aperture of 60 mm(h) x 40 mm (v). Taking the maximum β_v = 43 m we get for the minimum vertical beam emittance

$$\epsilon_v = \pi \frac{(20\,\text{mm})^2}{43\,\text{m}} = 9.3\,\pi\,\text{mm-mrad}$$

or a corresponding space charge limit of

$$N = 3.4\text{x}10^{13}$$

This enables us to adopt a more conservative pulse rate of 30 Hz. To get an intensity of 100 μA we will need $2\text{x}10^{13}$ p/pulse, still comfortably within the space charge limit. All other high intensity beam instabilities should still be avoidable or curable. The magnet cross-section will look roughly as shown below and the power consumption by the magnets will be about 2.5 MW.



C. Radiofrequency System

To get the cleanest injection and capture we adopt the synchronous injection/capture scheme in which the synchrotron rf frequency is synchronized to the bunch frequency of the beam from the injector. Assuming LAMPF is used as the injector the beam bunch frequency is then, 200 MHz (201.25 MHz to be exact). The synchrotron rf frequency at injection should then be 200 MHz or an integral fraction. We choose a frequency of $\frac{200\text{ MHz}}{4}$ = 50 MHz because one needs the 20 nsec time interval between beam bunches for time-of-flight experiments. Also 50 MHz is a good frequency in regard to the availability of power tubes and ferrites. Thus we have

Harmonic number = h = 153

Injection rf frequency = $f_i = hF_i = 50.3$ MHz

Final rf frequency = $f_f = hF_f = 59.6$ MHz

Range of frequency modulation = $\frac{\Delta f}{f} \cong 18\%$

Pulse rate = P = 30 Hz

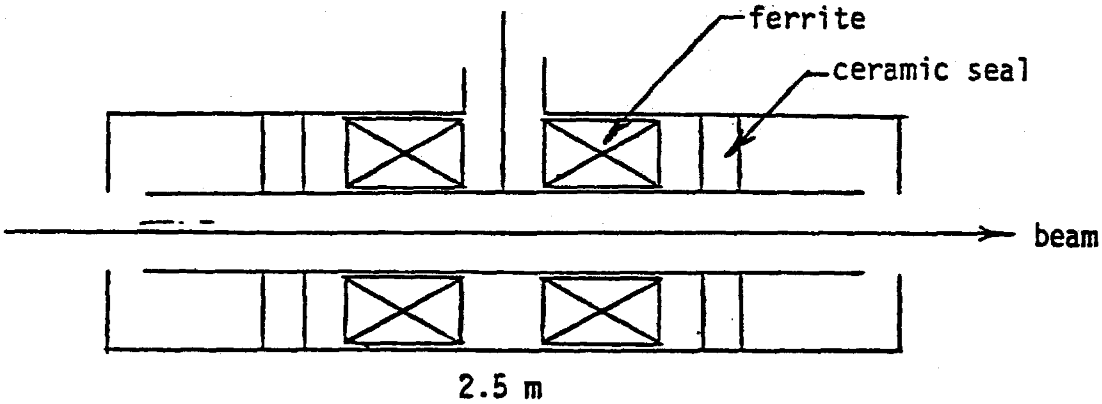
Max. energy gain per turn = $\left(\frac{dT}{dn}\right)_{max} = 2\pi R \left(\frac{dp}{dt}\right)_{max}$

$$= 2\pi R \times \pi P \times (p_f - p_i) = 3.7 \text{ MeV/turn}$$

Highest synchronous phase = $\phi_s = 60^o$

Max. peak rf voltage per turn = $\frac{3.7 \text{ MV}}{\sin 60^o} = 4.3$ MV.

The most straightforward hence the most reliable cavity is the 180° single drift-tube double-gap cavity shown below. The amount of ferrite needed for the 18% frequency modulation is not very large and a shunt resistance of ~100 kΩ should be obtainable.



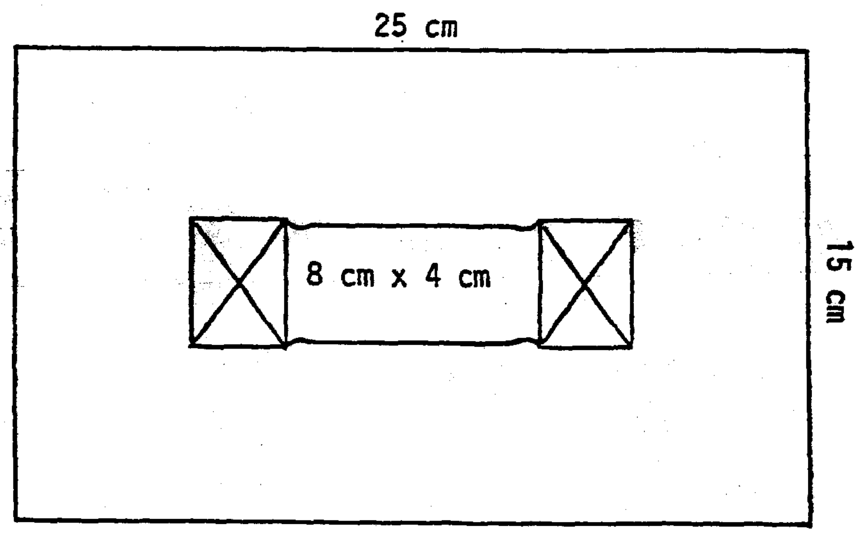
A peak voltage of 80 kV should be easy. With some pushing 160 kV may be attainable. At 80 kV/cavity we will need 54 cavities or 27 straight sections with 2 cavities in each straight section. The cavity loss will be 32 kW/cavity or 1.7 MW total.

D. Injector Requirements

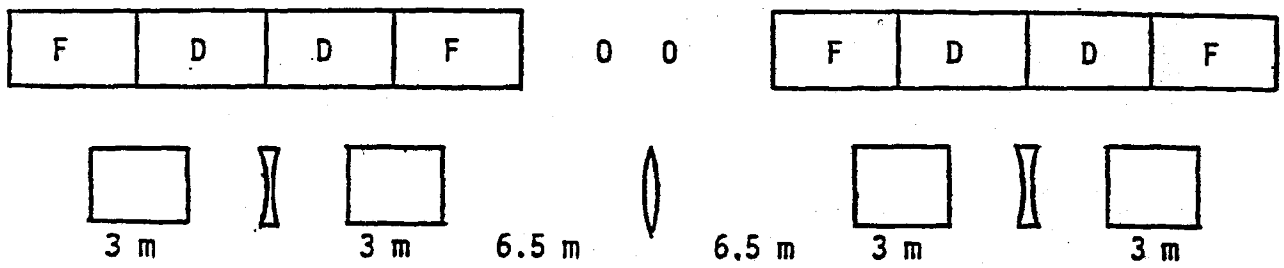
LAMPF is capable of a peak current of 12 mA when every one of the 200 MHz rf buckets is filled. With only one of every 4 buckets filled one gets only 3 mA or 5.5×10^{10} p/turn injected. Thus for 1×10^{13} p one needs to inject 180 turns corresponding to a pulse length of 0.54 msec and a circulating current of 180 x 3 mA = 0.54 A in the synchrotron. For 2×10^{13} p one needs 360 turns, 1.08 msec, and 1.08 A. With charge-exchange injection of H^- ions these large numbers of turns can be injected as has been demonstrated on the ANL-ZGS.[5]

E. Spill-Stretcher Ring

As was mentioned above superconducting coils could be used for this dc ring. But since the magnetic field does not have to be high one can still use the iron-yoke to shape the field. If we place two 3 m dipoles per cell the field strehgth only has to be 18.5 kG, still below the saturation of iron. The ideal cross-sectional geometry of the dipole is, then, the picture frame shown below.



The lattice now should have separated functions with dipoles and quadrupoles (represented as lenses) arranged as shown in the figure below.



The long straight section is now 13 m long (disregarding the quadrupole in the middle) which should be adequate for a 4π detector surrounding future colliding beams in the middle of the straight section.

The 16 GeV beam is fast injected, say, vertically from the synchrotron in one turn and slow extracted horizontally by, say, half-integer resonant extraction in $\frac{1}{30}$ sec. This way one should get a spill duty-factor close to 100%.

No rf is needed in principle. However some minimal rf at fixed frequency or with a very small range of frequency modulation may be advantageous for keeping some control over the beam during the slow extraction.

IV. COST ESTIMATE

The very crude cost estimate given below is no more than an educated guess since no detailed quantitative analysis was done. The estimates are conservative, some contingency may be considered included.

Fast Cycling Synchrotron	M$	
Magnet and P.S. Systems	20	
RF System	15	
Control and Diagnostics Systems	5	
Miscellaneous	10	
Vacuum, Injection, Extraction Transport, etc.		
Conventional Facilities	30	
		80
Spill-Stretcher Ring		20
	TOTAL	100

V. FUTURE OPTIONS

Other than additions and improvements to secondary and tertiary beams and to a variety of targets one can consider:

- $\bar{p}p$ colliding beams in the stretcher ring
- pp or ep colliding beams between the stretcher ring and the synchrotron.

In addition, the synchrotron can of course always be used as injector into a much higher energy accelerator.

This investigation was initiated at the prompting of Darragh Nagle. The synchrotron described resembles closely that outlined by him[7] in 1979. Technologically this is a realistic but unique and challenging project. When many hundred millions of dollars have been spent on gambles at the high energy frontier it is only sensible and wise to devote some resources on the high intensity territory where sober and intelligent evaluation has already indicated an abundance of interesting physics.

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